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Tire Pressure Monitoring System Overview

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Introduction

Most recent news reports of the giant tire and vehicle recall campaigns in the United States alarmed the public, and increased awareness about the impact of tires on passengers safety. Several research studies have been spawned in the wake of the recall activity, to better understand every variable in the interactive relationship between the car, the tire, and the passenger's safety. As it was in the past, safety remains one of the leading technology drivers in the automotive field. The area of research drawing the greatest attention and focus is the relationship between proper tire inflation and safety. Tire pressure is without question an important physical parameter to understand in this relationship. It dramatically impacts the way the tires grip the road, and thus the vehicle's performance. Therefore it stands to reason that being able to constantly monitor inflation levels in every tire, and communicate this information from the tire to the driver would be of value in the "safety equation". Enter the tire pressure monitoring system (TPMS)!

TPMS is a system that realistically could become a mandatory feature on all vehicles sold in the United States in the very near future. As a result of more fallout from the recent recalls, the US Congress has voted into effect a bill, called the TREAD Act[1]. This legislation empowers the National Highway Traffic Safety Administration (NHTSA) to develop a standard for low tire pressure monitoring that must be met by every auto manufacturer by the end of 2003. This has greatly accelerated the activity to understand and adopt this system. Of course in today's global automotive market, the impact of this legislation has been felt by every carmaker that wishes to preserve his sales and market share in the US.

Outside of the US market, these systems are expected to find their way into some of the more higher volume models very quickly as an optional feature. In addition to the safety aspects, proper tire pressure inflation improves gas mileage, as well as extends the life of the tires. While there is no legislation in place today outside of the United States, the consumer demand for these systems continues to grow quickly on its own.

Market considerations

Tire pressure monitoring systems (TPM) were implemented a number of years ago as a factory installed feature found only on high-end vehicles. Today many car manufacturers are making plans to offer these systems in their mid-range platforms as well. However, moving into the higher volume production models necessitates a considerable effort to make the TPMS a more economical feature. This requires not only the bill of material to be rethought, but also the entire system architecture must be redesigned for ease of integration with the other systems in the car, and a continued efficient production flow.

The semiconductor industry will play a leading role in this cost reduction effort. By offering highly integrated solutions, and by providing the right technologies to suit the application requirements, semiconductor suppliers can have an impact. TPMS, an embedded electronic system that is expected to be standard equipment in the next few years, is of a strategic interest for the Transportation Systems Group of Motorola's Semiconductor Sector. This Group is developing specific products, each compatible with the others, to offer a complete TPMS solution. The challenges that Motorola is addressing center on providing a cost-effective solution with reliable technology, and reducing the design cycles with their microcontoller-based technology and flexible design architecture.

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[1] Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act. Cf. section 12 "Tire pressure warning" for more details.

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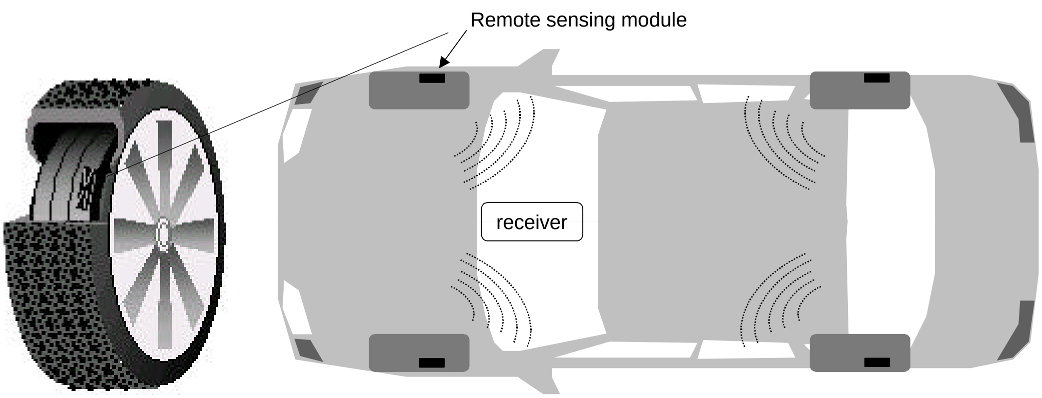
System overview

To do real time sensing of the exact pressure inside the tire, the sensing device must be located in the tire. This pressure measurement information must then be carried to the driver and displayed in the cabin of the car. This communications link is performed wirelessly, usually with a radio frequency (RF) transmission.

The remote sensing module is comprised of a pressure sensor, a signal processor, and a RF transmitter. The system must compensate pressure variations due to temperature. Hence a temperature sensor is also required in the system.



The power supply is provided by a long life battery that the embedded intelligence helps to manage as effectively as possible. Frequent replacement of the battery is out of question, and replacing the entire module is not a cost-effective solution for the car owners. It is for that reason, most of the existing specifications require a 10 years battery life.

The receiver could be either dedicated to TPM use, or shared with the other functions in the car. For instance, the receiver controller could be the existing dashboard controller, or the body controller. Or the RF receiver itself could be shared with the remote keyless entry (RKE) system since both systems are using the same frequency range. This “functional sharing” feature helps with the system cost, reduces design cycle time, and makes the TPMS feature easier to integrate into the automobile.

Remote Sensing Module (RSM)

Once mounted in the tire, the RSM is a stand-alone device. Its embedded intelligence has to independently manage the sensing functions, the measurement processing, the RF transmission, and the power management.

To address each of these functions, Motorola offers two new components as a solution. The first component, the TPMS Sensor, is an integrated monolithic chip device. It is comprised of both a temperature and pressure sensor with on board circuitry. The second component is a microcontroller and a RF transmitter, with both chips housed in the same package.

The TPM sensor:

The Motorola TPMS pressure sensor is a CMOS (Complementary Metal Oxide Silicon) based technology[2]. As a result of the need for low current consumption and robustness, a CMOS-based technology is the best-suited semiconductor technology for this application. Because CMOS is used, the standby mode uses less than .5 µA. Furthermore, because the sensor is in this mode most of the time, very low power consumption can be achieved.

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[2] B. Gogoi, K. Neumann, D. Hughes Jr., D. Odle, D. J. Monk, R. August, A. McNeil, J. Schmiesing, and J. Foerstner, "Integrated CMOS Capacitive Pressure Sensor," Patent Pending, 2000.

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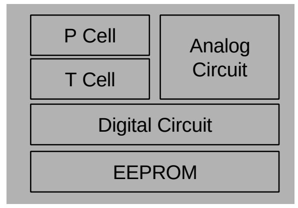
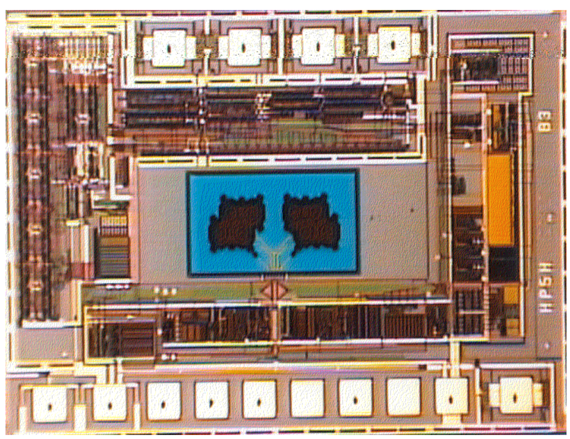


The Motorola TPM sensor block diagram

The pressure-sensing cell is capacitive and requires a C to V (capacitance to voltage) conversion stage. In addition to such analog functions, CMOS technology allows higher levels of integration like digital processing possibilities. One example of this is the sensor's built-in non-volatile memory to store calibration data as well as an ADC (Analog to Digital Converter), allowing a direct digital serial connection to the controller.

Moreover, the sensor internal state machine manages four different modes:
1. The standby mode: All analog and digital blocks are switched off, except an internal low frequency oscillator that sends a wake up pulse over an output pin to the controller periodically (every 6 seconds for example)
2. The pressure measurement mode: A mode in which the pressure cell, and the C to V converter are activated
3. The temperature measurement mode: In this mode the temperature cell (a PTC resistor) and its conditioning block are activated.
4. The read mode: After passing through one of the two above measurement modes, the measurement is stored in a sampling capacitor. The read mode activates the A to D converter and enables the controller to read serially the measurement.

These four modes are coded through two input pins controlled by the microcontroller. The coding is chosen so as to make the standby mode (in which both the sensor and the controller are asleep) coded with logic zero on both pins.



Photography of the Motorola CMOS TPM sensor chip

The Microcontroller:

Motorola has chosen the popular HC08 series microcontroller as the core for this customized product. The 68HC08RF2 device is a combination of an HC08 micro together with a RF transmitter in a single 32-pin LQFP package. The dual chip HC08RF2 has no internal connections between the controller die and the RF die, but the pinout is optimized to shorten the necessary external connections.

This HC08 version is ideally tailored for the TPMS application in terms of computing power, I/O resources, and power consumption. Furthermore, the 2 Kbytes of user flash memory with embedded charge pump allow designers to implement the necessary software routines to address the TPMS application's functional requirements. This software-based approach offers clear advantages over a discrete or ASIC-base solution, by providing more flexibility. It is also a more cost-effective approach.

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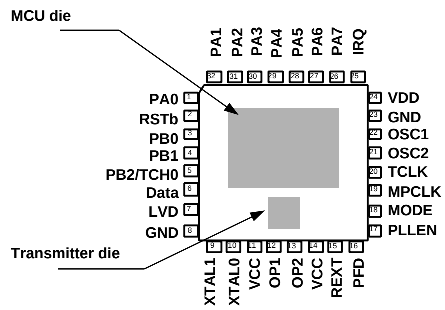
The RF transmitter is PLL based, addressing both ASK (amplitude modulation) and FSK (frequency modulation), its transmission rate is configurable up to 9600 baud. With a reference quartz oscillator of 13.56 MHz, the PLL is able to generate 315, 433, 868 MHz carriers covering the frequencies being used in different countries.

Because the microcontroller chip is fabricated in a standard CMOS technology, and a BiCMOS process is used for the PLL transmitter, a monolithic approach is not possible today. However, in the future these two technologies will converge, allowing for a single chip solution.

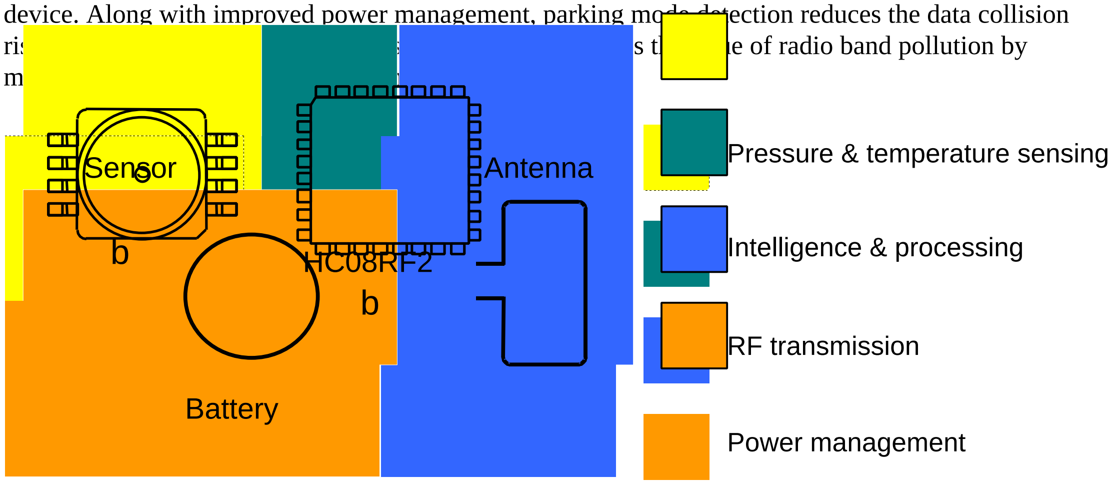


The HC08RF2 dual chip in LQFP 32 pin package

The System Architecture

The TPMS sensor is designed to work in full concert with the controller. This allows for some of the functions, like power management, to be shared. The HC08RF2 has advanced power management capabilities; thanks in large part to its built-in sleep mode, and its battery supervisor. In addition, the HC08RF2 controls the sensor-state by setting the operating modes as mentioned earlier. When the sensor is set in standby mode, its internal low frequency oscillator periodically wakes up the controller. After each wake up, the controller may run different and configurable tasks according to the software program. After two wake up pulses, the micro-controller is in the STOP mode. All functions are disabled to minimize the power consumption, and only an external stimulus can wake up the system again.

To improve the battery management, an inertial switch can be employed to detect the parking mode. In fact, in parking conditions the RF transmissions can be stopped or greatly reduced. This switch can be either in micromachined silicon and integrated with the sensor, or a mere electromechanical external device. Along with improved power management, parking mode detection reduces the data collision ri s t e of radio band pollution by m



The remote sensing module functional partitioning

The RF circuitry is designed for optimal use with the HC08. The data transmission uses register transfer techniques to minimize the CPU effective time used, therefore minimizing the power consumption.

Demonstration designs have shown that a simple printed antenna, though far from the wavelength in dimensions, reliably attains the necessary radiated power to reach the receiver module.

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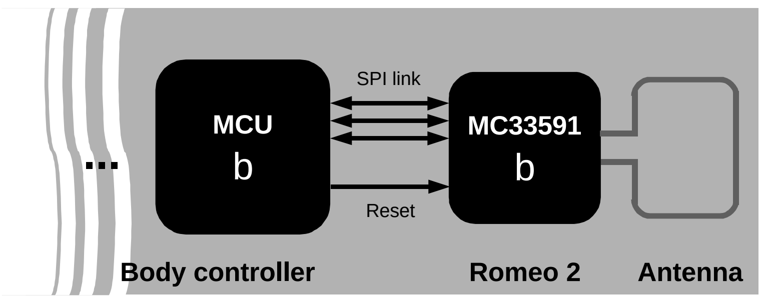
The RSM must be as small and lightweight as possible since it is mounted inside the tire. An oversized RSM could result in wheel imbalance. The approach of using a highly integrated system based on only two components and a small battery, with minimal power consumption, address this mechanical requirement.

TPMS suppliers may offer variations of the basic solutions in order to differentiate themselves in the market. The main advantage of a microcontroller-based architecture lies in the software. It is the major differentiator between manufacturer A and manufacturer B even if both are using the same “standard” set of components. This approach allows significant cost reductions not only in the bill of material, but also in terms of development cost. Furthermore, upgrading or adding functionality becomes easier since software modifications require less development and qualification work.

The Receiver

While the RSM is a relatively new concept requiring a significant innovative effort, the receiver module, on the other hand is comparatively less involving. The RF receiver is based on more established techniques used for a number of years in the Remote Keyless Entry system (RKE). A single receiver can be shared between both the RKE and TPM systems since the same transmitting format is used in both. In fact, the HC08RF2 discussed earlier is also widely adopted in RKE systems, used for signal transmission from the key. Clearly, such reuse dramatically reduces the function cost. However, it also requires a more in depth knowledge of high-level systems architectures.

In most architecture, the receiver is integrated within the body controller. That processor may also have many other functions to supervise. Therefore CPU time sharing between the different functions is vital. The TPM function must use as little CPU time as possible, and to achieve this, a highly integrated RF receiver is required.



The RF receiver as part of the body controller

To address this, the MC33591, also called Romeo II, from Motorola has been designed with that issue in mind. Motorola has developed this RF receiver in order to provide a comprehensive RF link that is integrable in RKE and TPM systems with Romeo II at one end, and the HC08RF2 at the other end. Thanks to its embedded RF decoding and data registers, Romeo II minimizes the communication with the receiver microcontroller. The MCU is not called upon until a valid data frame is received, validated, and stored by the Romeo II device. Moreover, the receiver remains fully configurable by the microcontroller through its serial link.

Tire Identification

TPMS is a warning system designed to inform the driver about the operating state for each tire. This information could be more or less comprehensive depending on the system’s level of complexity. For example, the system could tell the driver the exact tire pressure value, or provide simple binary information to warn him when the pressure is outside a preset safe operating range.

At the other extreme, the simplest system configuration does not identify each tire individually. The receiver is not able to locate each transmitter to tell the driver which of the four tires is sending a low-pressure warning. He is only warned to check tire pressure.

There are basically two ways to perform the tire identification. The simplest is the manual initialization performed in the factory, or in the garage each time a tire is replaced or moved (rotated). The second

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method is by automatic identification. Using this method, the system locates each tire automatically by a learning procedure that is activated regularly, or upon request.

Manual Initialization

Each RSM sends its individual identifier with the transmitted data. During the initialization procedure the receiver stores the four identifiers (five, if the car is equipped with a spare tire carrying a RSM). The operator then tells the receiver which wheel each identifier belongs to (i.e. front right = FR, rear right = RR, etc.) by use of a programming interface. This interface is commonly connected to the receiver module, a data bus, or by generating a transmission from each RSM remotely. In the case of the remote transmission method, the operator places the receiver in the initialization mode and activates the transmission successively on the four RSM's in a preset order known by the receiver.

Since it is not directly accessible, the RSM could be activated manually through a magnet placed against the tire. This closes a reed relay, which activates the remote RF transmission.

Automatic Identification

In the case of manual initialization, the car owner must go to an authorized garage for the ID initialization, unless of course he does it himself. The automatic identification method allows the owner to avoid such hassles.

As expected this auto-ID does require additional features and a smarter control unit, that dramatically impacts the system cost. Hence, TPMS manufacturers have made noticeable efforts to implement this feature at a minimum cost. It has resulted in a huge amount of intellectual property, and a number of patents dealing with auto-ID.

Here are a few examples of the different approaches:

1. Dedicated RF receiver for each wheel: Probably the most reliable solution. By implementing a receiver near each wheel, the control unit can identify and locate effortlessly each tire. The receivers must be connected to the control unit through dedicated wires or a bus. Identification with this method is immediate and reliable. To date this solution has been adopted only for high-end cars because of its prohibitive cost. A patented technique[3] using four antennas connected to a single central receiver significantly lowers the cost of this solution. A RF multiplexer inserted between the antennas and the receiver makes the signal selection so as to identify the origin of the transmissions.
2. Inertial sensing of speed: An accelerometer implemented in each RSM is used to determine wheel speed. This information is then sent to the receiver through RF. A sophisticated algorithm combines this speed information, with information coming from other systems (ABS, ESP, etc.), and calculates the tire position by exploiting the fact that in a curve the inner wheels rotate at a slower speed. This approach requires an additional component, that being the accelerometer. On the other hand, this sensor could be used to optimize the power consumption at the RSM level by adapting the RF transmission periodicity to the car speed, and setting it to the minimum in the parking mode. Finally, the learning procedure is long because it is based on statistical processing, and it is quite unreliable since it is active in road turns only.
3. Amplitude analysis of the RF signals: In driving conditions, the reception level of each RSM signals by the receiver varies periodically according to the tire's rotation. This variation causes an amplitude modulation that could be detected at the receiver level, the wheel speed is then deduced. A similar algorithm as the one used above in method #2 calculates each tire position. This solution seems very cost effective, yet its feasibility has not been demonstrated.
4. Bi-directional RF links: This solution allows an immediate and reliable identification. Moreover, since the receiver can communicate with each RSM, the power management could be greatly improved. In fact, while in standard one way RF transmission, the RSM is totally deaf and transmits the pressure measurements periodically and asynchronously from the other RSM's. A bi-

[3]U.S. Patent #6 034 597 (Mar.2000): N. Normann, N. Oschelbronn, G. L. Schulze, Ispringen, R. Kessler, Pfinztal, A. Kuhnle, Knittlingen, "Process for evaluating the signals from a tire pressure monitoring system".

directional RF link enables RSM's to send their measurement only upon request avoiding collisions and allowing better power management.

There may very well be several possible ways to perform tire identification automatically. The ID feature is expected to be in mass production in the next generations of TPM systems. Until then each system supplier closely guards his unique plans to address tire ID. To date, there is no way to implement a reliable automatic identification method without generating additional cost. The market will decide whether this feature is in fact affordable.

Media Protection

Imagine a place where the temperatures could reach as high as 150 °C, or as low as -40 °C. A place where the atmosphere is infested with corrosive chemicals, and you are constantly subjected to acceleration ranges of 1000 g with crests to 2000 g (this is 2000 times your weight!). Welcome to the world of a TPMS remote sensing module!

The sensor is by far the most exposed component in the module since it must be in contact with air to sense the surrounding pressure. Thus, special care is put into designing the module's mechanical housing so as to optimize the protection of the most sensitive component. A potting is typically laid onto the PCB to protect its components. However because the pressure sensor must be in contact with the air in the tire, it requires special protection against aggressive media such as liquids, dust, and gases all present inside the tire.

Most of the existing media protection solutions are implemented at the module level, because they are using sensors with unprotected standard packages. Motorola has integrated this protection in the sensor package[4]. Therefore a new package, dedicated for the TPMS application, has been designed. This package offers manufacturers easier mechanical integration and lower system's cost since no additional protection is required at the module level.

The media protection is based on a Teflon filter, which is sealed onto the package. Extensive tests demonstrated that this concept efficiently protects the sensor die against any chemical that could be present in a tire like mounting paste, or even moisture and humidity. These specific Teflon filters are, in fact, manufactured to be both hydrophobic (as expected with Teflon) and oleophobic, and the microporous structure of the filter repels liquids and vapors while allowing the passage of gases.

For the Future

The next generation TPM system will have a new and different set of requirements than today's systems. While the destiny for TPMS clearly appears to be headed towards becoming standard equipment, this system will most likely offer an increasing number of features in line with the industry's efforts towards safety. Adding more sensors or components may not necessarily be the method of providing many of those additional future features. Combining different information sources could be the path taken to meet these needs. TPM is in fact, destined to become more integrated into the vehicle architecture. New synergies similar to the one discovered between RKE and TPMS will be generated, leading to more interaction with other systems such as braking or stability control.

Furthermore, the automotive industry is considering wireless links as an alternative to simplify the increasing complexity of harnesses. For instance, the Bluetooth technology has the interest of many car manufactures today. On this assumption, the TPMS radio-frequency link could be integrated into such a wireless general bus in the future.

According to some market projections, TPMS will explode in the coming 5 years. The worldwide estimated annual production rate for remote sensing modules is in the range of 250 million units! If these are battery-powered modules, this raises some very serious environmental issues regarding end-of-life battery recycling. Alternative battery-less solutions based on inductive coupling are being investigated and considered now to address these future concern. This inductive coupling approach would also help solve the tire identification issue.

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[4] S. Petrovic, D. J. Monk, and H. J. Miller, "Teflon Filters for Media Compatible Pressure Sensors", Patent pending

There are few specialized manufacturers currently playing a leading role in TPMS development. Their role is an important one, because they are shaping the future for this application. With their system level expertise and technology leadership, they will enable the car manufacturers to be more actively involved in the design and technology choices. The reality of the assumptions mentioned above hinge on the major architecture choices. Such decisions are ultimately up to automakers because those choices impact the entire car design.

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